Spectral Turbulence Versus Time-Domain Analysis of Signal-Averaged ECG Used for the Prediction of Different Arrhythmic Events in Survivors of Acute Myocardial Infarction

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Spectral Turbulence SAECG After MI. ***Introduction:*** **Spectral turbulence analysis of the signal-averaged ECG (SAECG) combines spectral analysis with statistical evaluation of spectrograms of individual parts of the QRS complex. It has been suggested that it may be superior to conventional time-domain analysis of the SAECG.**

Methods and Results: **This study compared the power of conventional time-domain (40 to 250 Hz) and spectral turbulence analyses of SAECG for the prediction of cardiac death, ventricular tachycardia, sudden arrhythmic death, and arrhythmic events (ventricular tachycardia or fibrillation, and/or sudden arrhythmic death) after acute myocardial infarction in 603 patients. The population excluded patients with bundle branch block and other conduction abnormalities. During the first 2 years of follow-up, there were 40 cardiac deaths, 21 cases of ventricular tachycardia, 11 sudden arrhythmic deaths, and 29 arrhythmic events. The positive predictive accuracy of spectral turbulence analysis was significantly higher than time-domain analysis for cardiac death at most levels of sensitivity (e.g., 26% vs 20% at 40% sensitivity, $P < 0.05$). The positive predictive accuracies of the two techniques were not statistically different for the prediction of ventricular tachycardia. For the prediction of sudden arrhythmic death and arrhythmic events, the positive predictive accuracy of spectral turbulence was better than that of time-domain analysis only at the higher levels of sensitivity (9% vs 2%, $P < 0.001$ for sudden arrhythmic death at 60% sensitivity, and 14% vs 11%, $P < 0.05$ for arrhythmic events at 60% sensitivity).**

Conclusions: **Spectral turbulence analysis is essentially equivalent to time-domain analysis for the prediction of arrhythmic events after myocardial infarction. However, it performed significantly better than time-domain analysis for the prediction of cardiac death.** *(J Cardiovasc Electrophysiol, Vol. 7, pp. 583-593, July 1996)*

signal-averaged electrocardiogram, time-domain analysis, spectral turbulence analysis, risk stratification, myocardial infarction

Introduction

The conventional time-domain analysis of the signal-averaged ECG (SAECG) concentrates on the assessment of microvolt signals at the end of the high-gain QRS complex.[1] The low-amplitude signals at the end of the QRS complex are believed to reflect myocardial areas of slow conduction that might have arrhythmogenic properties.[2] The diagnosis of late potentials performed in this way was repeatedly shown to recognize patients who present with ventricular tachycardia[3,4] and to identify those survivors of acute myocardial infarction who are at high risk of arrhythmic complications.[5-10]

The limitations of the conventional analysis of SAECG imposed by the analysis of the terminal portion of the averaged QRS complex have also

Dr. Copie is supported by a grant from the Fédération Française de Cardiologie and Dr. Hnatkova by the British Heart Foundation.

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Manuscript received 29 March 1994; Accepted for publication 18 March 1996.

been well recognized.[11-13] If the myocardial region of slow conduction is activated early, the corresponding "late" microvolt signals will be hidden within the QRS complex and will not be detected by time-domain SAECG analysis. This limitation is believed to account for the fact that the incidence of conventionally detectable SAECG pathologies is higher in patients with ventricular tachycardia following inferior infarction than in those with ventricular tachycardia after anterior infarction.[7,14,15] Consequently, it has been suggested that a detailed analysis of the complete high-gain QRS complex might be, in some respects, superior to the conventional time-domain approach. Several pilot studies that included detailed spectral analysis of the total QRS complex[16-18] as well as its wavelet decomposition[19-21] have been conducted.

Spectral analysis of the complete QRS complex is the basis of the so-called "spectral turbulence analysis" in which it is combined with a statistical evaluation of spectrograms of individual parts of the QRS complex.[16] This technique is now commercially available and has been shown to identify patients with ischemic ventricular tachycardia.[16] However, only two recent studies have examined the value of spectral turbulence analysis for the prediction of arrhythmic events in post-myocardial infarction patients.[22,26] Moreover, no attempts have been made to optimize spectral turbulence criteria for risk stratification after myocardial infarction. Therefore, the aim of this study was to compare the time-domain and spectral turbulence analyses of SAECG for risk stratification after myocardial infarction, and to establish new criteria for spectral turbulence applicable to postinfarction risk stratification.

Methods

Patient Population

The study population consisted of 603 patients aged ≤ 75 years who were admitted to our hospital with acute myocardial infarction, diagnosed using previously published criteria.[23] The patients were enrolled from January 1987 through June 1993. The study population did not include patients with a typical pattern of left or right bundle branch block, or a nonspecific intraventricular delay with QRS duration above 120 msec (assessed from standard ECGs without analyzing the SAECG records), with permanent pacemaker implant, or with other significant disease likely to increase mortality. Patients unable to participate in the follow-up program of our institution were also not included in the study population. A total of 285 patients were excluded from analysis because they did not have an SAECG recorded or one technically suitable for analysis (that is, with a noise level ≤ 1.0 μV). The clinical characteristics of the 603 patients of the study population and of the 285 patients excluded from analysis are shown in Table 1. No difference between these two populations was statistically significant.

All patients of the study population have been followed for at least 2 years. As a rule, every patient admitted to our hospital with an acute myocardial infarction is enrolled in the follow-up research program and seen in the outpatient clinic at 6 weeks, at 3, 6, and 12 months after the index infarction, and annually thereafter. Patients with nonfatal follow-up events are seen immediately after the event. Out-of-hospital fatal events are classified according to post mortem and/or details obtained from family members and the relevant general practitioner. Regularly and at special occasions, as was the case with this study, telephone contact is made with patients not seen recently. The follow-up of patients included in this study ranged from 2 to 8 years.

If a patient had two myocardial infarctions, only the first one was considered. During the first 2 years after hospital admission, 49 patients died and 21 presented with sustained symptomatic ventricular tachycardia. Forty of the deaths were classified as cardiac and 11 as sudden arrhythmic deaths. Sudden arrhythmic death was defined as death within 1 hour of the symptoms in patients with no evidence of acute congestive heart failure or acute ischemic event at clinical or postmortem examination. All sustained symptomatic ventricular tachy-

TABLE 1
Clinical Characteristics of the Study Population and of the Population Not Included in the Study

	Study Population (n = 603)	Patients Excluded From Analysis (n = 285)
All-cause mortality (%)	8	10
Age (mean ± SD)	57.3 ± 8.6	59.2 ± 10.7
Sex ratio (% of males)	81	78
Anterior MI (%)	48	52
Previous MI (%)	15	16
β-blockers on discharge (%)	39	36
Thrombolysis on admission (%)	63	58

MI = myocardial infarction.

cardias were electrocardiographically documented on standard ECG recording, and usually during emergency admission to the hospital. Four patients were also resuscitated from ventricular fibrillation.

Consequently, the endpoint categories considered in this study were: (1) cardiac death (n = 40); (2) sustained symptomatic ventricular tachycardia (n = 21); (3) sudden arrhythmic death (n = 11); and (4) arrhythmic events, which included sudden arrhythmic deaths, ventricular tachycardia, and ventricular fibrillation (n = 29). If a patient had more than one event (e.g., ventricular tachycardia, sudden arrhythmic death, and cardiac death), he was counted as one event in each category but also only as one event in the combined arrhythmic event endpoint. Therefore, the arrhythmic event category was composed of 17 patients who had a ventricular tachycardia alone, 1 patient who had a ventricular fibrillation alone, 6 patients who had a sudden arrhythmic death alone, 4 patients who had a sudden arrhythmic death and a ventricular tachycardia, and 1 patient who had a sudden arrhythmic death and a ventricular fibrillation.

SAECG Recordings

An SAECG was recorded from each patient before hospital discharge at a median of 8 days (range 5 to 11) after admission for acute myocardial infarction. The recordings were made from the orthogonal X,Y,Z leads using a Model 1200 EPX Arrhythmia Research Technology (Austin, TX, USA) recorder. A mean of 237 cardiac cycles was averaged, and in all patients a noise level $\leq$ 1.0 μV was achieved (recomputed for the vector magnitude of orthogonal leads at Del Mar [Del Mar Avionics, Irvine, CA, USA] filter settings of 40 to 250 Hz). The noise level was $\leq$ 0.5, $\leq$ 0.6, and $\leq$ 0.7 μV in 49%, 23%, and 21% of the total population, respectively.

All recordings were stored on a personal computer and subsequently analyzed using the CEWS software package from Del Mar Avionics (Model 183). The time-domain analysis of each recording was performed at high-pass filter settings of 40 Hz using the Del Mar filter. Three conventional time-domain indices were calculated: the duration of the total QRS complex (tQRS); the duration of the terminal low-amplitude signals $<$ 40 μV (LAS 40); and the root mean square voltage of the last 40 msec of the QRS complex (RMS 40).

The spectral turbulence analysis was performed using the averaged X+Y+Z lead on the segment starting 25 msec before the QRS onset and ending 125 msec after the QRS offset. This segment was divided into overlapping 24-msec slices in 2-msec steps. Each time slice was multiplied by a 4-pole Blackman-Harris window and analyzed using the fast Fourier transformation. In order to detect abrupt changes in activation wavefront velocity caused by myocardial regions of abnormal conduction, five statistical parameters were computed: mean peaks per slice (MPPS); low-segment correlation ratio (LSCR); intersegment correlation mean (ISCM); intersegment correlation standard deviation (ISCSD); and spectral entropy (SE).

Data Analysis

Statistical Comparison

The individual indices of time-domain and spectral turbulence analyses were compared in groups of patients with and without each endpoint, i.e., in patients who did and did not die of cardiac cause within the first 2 years of follow-up, in patients who did and did not present with sustained ventricular tachycardia, in patients who did and did not die of sudden arrhythmic death, and in patients who did and did not present with an arrhythmic complication. The values of the indices were compared using a nonparametric *U*-test; a P level $\leq$ 0.05 was required for statistical significance.

Positive Predictive Characteristics

The power of spectral turbulence indices to predict the endpoints of the study was examined by computing the positive predictive characteristics (PPCs), that is, curves expressing the dependence of positive predictive accuracy (i.e., the ratio [true positive]/[true positive + false positive]) on sensitivity. Using a previously described algorithm,[24] the dichotomy limits (that is, the individual thresholds of abnormality of each SAECG parameter) were changed in a systematic fashion in order to examine all possible levels of sensitivity, and for each level of sensitivity, the maximum achievable positive predictive accuracy was established. This algorithm was applied separately to the prediction of each endpoint in the following way. Individual PPCs were computed for each of the five spectral turbulence indices separately, then PPCs were computed for each pair, triplets, etc., of the five indices. When calculating the PPCs for pairs, triplets, etc., of spectral turbulence indices, different strategies were also considered, which required 1 of 2 or 2 of 2 (in cases of pairs), or 1 of

3, 2 of 3, or 3 of 3 (in cases of triplets), etc., indices to be out of the dichotomy range. In the cases of multifactorial PPCs, the optimum PPC also included the optimum choice of these possibilities.

For the four endpoints, the best PPC achievable with the spectral turbulence variables was also statistically compared with the optimum PPC that was achieved with the conventional time-domain variables. The optimum time-domain PPC was based on the strategy that required 2 of 3 variables to be out of the dichotomy range in order to note a test positive outcome.[15] The statistical comparison of two PPCs was performed at several levels of sensitivity. For a given level of sensitivity, the dichotomy limits of spectral turbulence indices and of the time-domain indices giving the highest positive predictive accuracy were established. Then the subpopulation of the complete population was established for which the spectral turbulence and the time-domain findings (using the established dichotomy limits) did not agree. That is, the subpopulation was composed of those patients who were test positive with respect to one of the spectral turbulence or time-domain analyses, and test negative with respect to the other. If the number of such patients for whom the time-domain finding was correct (i.e., test positive for patients with the endpoint and test negative for patients without the endpoint) was significantly higher than the number of patients for whom the spectral turbulence analysis finding was correct, the performance of the time-domain analysis was taken as significantly better and vice versa. The number of patients for whom spectral turbulence was correct and time-domain analysis incorrect (and vice versa) were compared using a standard sign test.

Comparison with Previously Published Criteria

Each SAECG analysis was classified as positive or negative according to previously published criteria. The time-domain SAECG was considered abnormal when at least 2 of 3 variables were out of range[25]: tQRS > 114 msec; LAS 40 > 38 msec; and RMS 40 < 20 μV. The spectral turbulence analysis was considered abnormal when at least 3 of the 4 indices previously described were abnormal[16]: LSCR > 73; ISCM < 92; ISCSD > 105; and SE > 14.

Based on the computations of PPC curves, adjusted criteria for the five spectral turbulence indices (MPPS and the four previously described) were calculated. These new criteria were compared in terms of sensitivity, specificity, positive predictive accuracy, negative predictive accuracy, and total predictive accuracy (i.e., the percentage of patients with either true-positive or true-negative results) with standard time-domain and spectral turbulence analyses.

Survival Analysis

Kaplan-Meier survival curves were computed for the probability of event-free survival in patients with normal and abnormal time-domain SAECG,[25] in patients with normal and abnormal spectral turbulence analysis according to previously published criteria,[16] and in patients with normal and abnormal spectral turbulence analysis according to new criteria as mentioned in the previous section. The survival analysis was performed for the probability of the following follow-up events: (1) cardiac mortality; (2) sustained symptomatic ventricular tachycardia; (3) sudden arrhythmic death and/or resuscitated ventricular fibrillation; and (4) arrhythmic events (that is sudden death and/or ventricular tachycardia and/or ventricular fibrillation).

Although other analyses of the study considered a fixed follow-up period of 2 years that was completed for all subjects of the study population, the analysis of survival curves utilized the complete follow-up data available. That is, events that occurred more than 2 years after the index infarction and that were not considered in other analyses were included into the computation of survival curves.

A log-rank test was used to compare survival curves of patients with positive and negative SAECG findings according to different diagnostic criteria.

Relation Between SAECG Analysis and Left Ventricular Ejection Fraction

The relation between SAECG according to spectral turbulence or time-domain analysis and left ventricular ejection fraction was tested in the following way. A total of 516 patients included in the study also had determination of left ventricular ejection fraction. Mean left ventricular ejection fraction was compared among patients with a positive spectral turbulence or time-domain SAECG using a standard t-test. Left ventricular ejection fraction was also compared in patients with a negative SAECG according to spectral turbulence or time-domain analysis. Classification of SAECGs as positive or negative was made according to standard time-domain criteria and our new spectral turbulence criteria.

Relation Between SAECG Analysis and the Site of Myocardial Infarction

The relation between the site of myocardial infarction and results of SAECG was analyzed in the following way. The incidence of anterior myocardial infarction was compared in patients with a positive spectral turbulence SAECG according to our new criteria, and in patients with a positive time-domain SAECG using a χ^2-test. The same comparison was performed in patients with a negative SAECG.

Results

Individual Spectral Turbulence and Time-Domain Indices

The comparison of individual spectral turbulence and time-domain indices in patients with and without endpoints is shown in Table 2. In patients with and without ventricular tachycardia, P values were lower for time-domain variables than for spectral turbulence variables. The contrary was true for patients with and without cardiac death, with P values being lower for spectral turbulence indices than for time-domain indices. Time-domain parameters were not statistically different in patients with and without sudden arrhythmic death, but spectral turbulence indices ISCM and ISCSD were. For patients with and without an arrhythmic event, the P values appeared equivalent for time-domain and spectral turbulence indices; only MPPS was not statistically different.

PPCs

The optimum PPC curves achieved with 1, 2, 3, 4, or 5 spectral turbulence indices are shown in Figure 1. In terms of the PPC curves, MPPS was the single best spectral turbulence variable for the prediction of each endpoint. For all four events, the best PPC curve was obtained with the combination of the five indices, with the strategy requiring at least three of them to be abnormal for a positive diagnosis. The optimum time-domain PPC curves were obtained with the strategy requiring at least 2 of the 3 indices to be abnormal for a positive diagnosis. As evidenced in Figure 1, spectral turbulence analysis was a better predictor of cardiac death than time-domain analysis. Time-domain and spectral turbulence analysis performed similarly for the prediction of arrhythmic events and ventricular tachycardia. For the prediction of sudden arrhythmic death, spectral turbulence appeared to perform better at high sensitivity levels, whereas time-domain analysis performed better for sensitivity levels below 40%.

Statistical comparisons of time-domain and spectral turbulence PPC curves at selected levels of sensitivity are presented in Table 3. Spectral turbulence analysis performed statistically better than time-domain analysis for the prediction of cardiac death. The two SAECG analyses were equivalent for the prediction of ventricular tachycardia. For the prediction of sudden arrhythmic death and arrhythmic events, the positive predictive accuracy of spectral turbulence analysis was statistically better than time-domain analysis only at the highest levels of sensitivity.

TABLE 2
Comparison of SAECG Indices in Patients With and Without Events

	Cardiac Deaths (n = 40)	Ventricular Tachycardia (n = 21)	Sudden Arrhythmic Death (n = 11)	Arrhythmic Events (n = 29)	No Endpoint (n = 549)
tQRS (msec)	103.8 ± 19.6**	106.5 ± 19.7**	101.7 ± 26.5	101.9 ± 20.3*	95.2 ± 17.6
RMS 40 (μV)	28.0 ± 23.0	21.6 ± 19.6**	34.7 ± 31.1	27.1 ± 25.2*	31.1 ± 20.3
LAS 40 (msec)	37.4 ± 17.3*	42.4 ± 19.3**	40.3 ± 24.5	39.2 ± 18.7*	31.0 ± 12.7
MPPS	33.7 ± 7.7**	33.6 ± 8.6	32.4 ± 8.5	32.3 ± 8.4	31.4 ± 5.4
LSCR	74.2 ± 7.1**	73.7 ± 8.8*	74.3 ± 5.1	73.6 ± 8.0*	72.0 ± 5.5
ISCM	91.7 ± 1.6***	91.9 ± 2.0	91.6 ± 1.2*	91.8 ± 1.8*	92.5 ± 1.3
ISCSD	115.7 ± 26.2**	112.9 ± 32.0	120.0 ± 17.4**	114.2 ± 28.2*	103.3 ± 23.4
SE	15.8 ± 4.4**	15.9 ± 4.4*	15.2 ± 4.2	15.3 ± 4.2*	13.8 ± 3.5

This table shows mean values ± SD of time-domain and spectral turbulence indices in patients with and without endpoints for each of the four categories. Note that the statistical comparison of the mean values was performed using a standard *U*-test between the patients with and without the event (that is, not between the patients with the event and without any event, as shown in the columns of the table).
* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. See text for abbreviations of the SAECG indices.

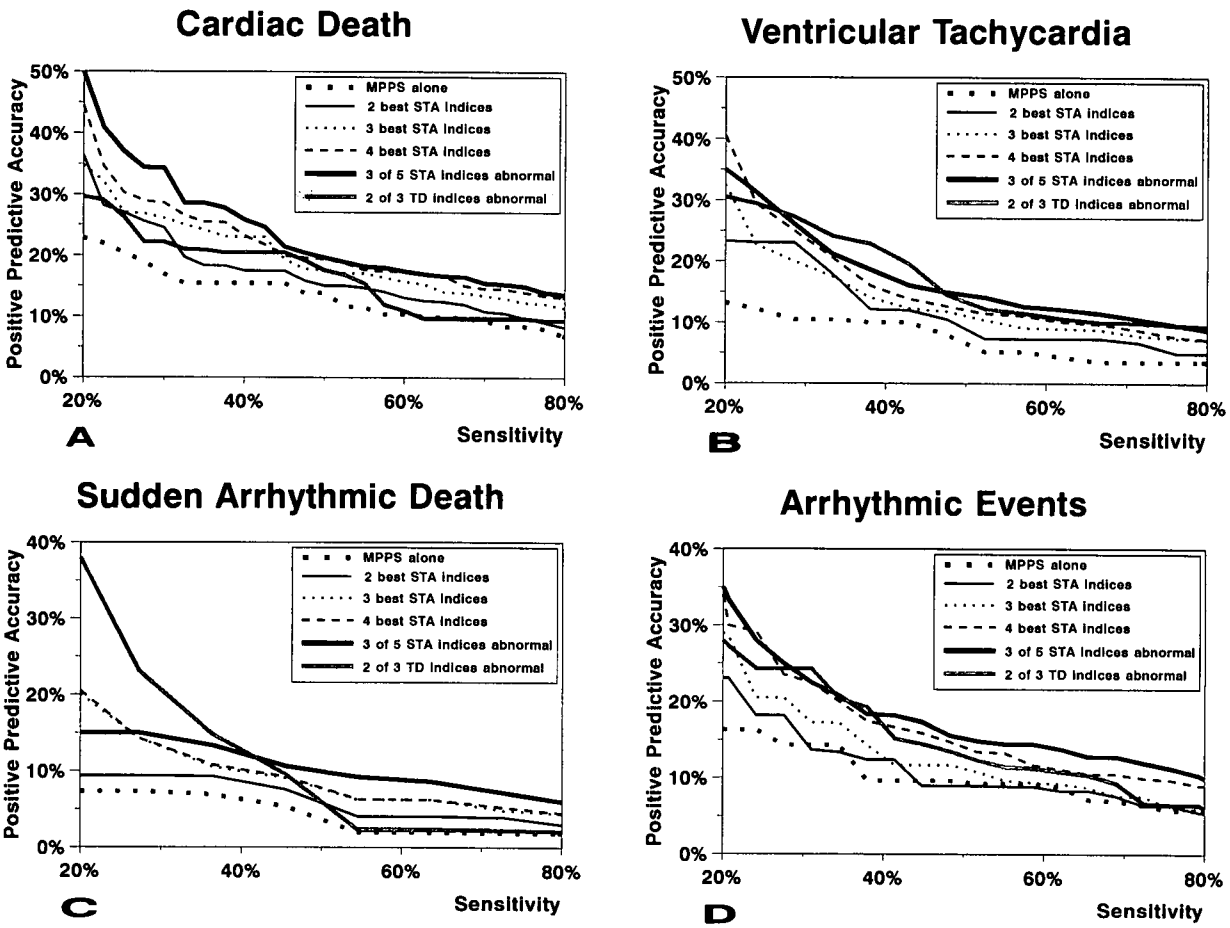

Figure 1. *Optimum positive predictive characteristics achieved with the combinations of spectral turbulence and time-domain indices, for the prediction of cardiac death (A), ventricular tachycardia (B), sudden arrhythmic death (C), and arrhythmic events (D). The combinations of 2, 3, and 4 optimum indices of spectral turbulence analysis (STA) were dependent on the stratified endpoint (see text for details). MPPS = mean peak per slice; TD = time-domain.*

TABLE 3

Comparison of the Positive Predictive Accuracy Achieved with Time-Domain and Spectral Turbulence Analysis at Selected Levels of Sensitivity

	Cardiac Death		Ventricular Tachycardia		Sudden Arrhythmic Death		Arrhythmic Events	
Sensitivity (%)	PPA TD (%)	PPA STA (%)	PPA TD (%)	PPA STA (%)	PPA TD (%)	PPA STA (%)	PPA TD (%)	PPA STA (%)
30	22	34*	27	26	23	15	24	23
40	20	26*	23	19	15	13	15	18
50	18	20	12	14	3	9***	12	15
60	11	17***	11	12	2	9***	11	14*
70	9	15***	9	11	2	7***	9	13***

Asterisks indicate statistical comparison between the PPA values achieved by the time-domain and the spectral turbulence analysis (see text for details). Time-domain analysis was never significantly superior to spectral turbulence analysis in these tests.

PPA = positive predictive accuracy; STA = spectral turbulence analysis; TD = time-domain.

* $P < 0.05$; *** $P < 0.001$.

Definition of New Criteria

The computation of the PPCs of spectral turbulence analysis enabled us to define optimal criteria for risk stratification after myocardial infarction. These criteria are as follow: MPPS > 36; LSCR > 68; ISCM < 90; ISCSD > 136; and SE > 13, with the strategy requiring at least three indices to be positive for a positive diagnosis. The diagnostic performances of these new criteria are compared with the previously available spectral turbulence criteria and with the standard time-domain criteria in Table 4. With the new criteria, spectral turbulence analysis had a better total predictive accuracy than time-domain analysis for all four endpoints.

Survival Analysis

Kaplan-Meier survival curves for different follow-up events are presented in Figure 2. The distinction of cardiac death and arrhythmic event probability in patients with normal and abnormal SAECG according to standard time-domain criteria was slightly less powerful compared to that between patients with normal and abnormal spectral turbulence analysis according to the new criteria. For both these event categories, the distinction between patients with normal and abnormal spectral turbulence analysis according to the previously published criteria was poorer (Fig. 2, panels A and D).

The time-domain analysis was superior to the spectral turbulence analysis in differentiating the sustained symptomatic ventricular tachycardia-free survival (Fig. 2, panel B). On the contrary, spectral turbulence analysis (classified according to both the previously published and, especially, the new criteria) was more powerful in differentiating the probability of sudden arrhythmic death and/or ventricular fibrillation-free survival, compared to the time-domain analysis (Fig. 2, panel C). The difference between the positive and negative time-domain analysis survival curves was not statistically significant in this case.

Relation Between SAECG Analysis and Left Ventricular Ejection Fraction

Ejection fraction was lower in patients with a positive spectral turbulence SAECG according to our new criteria, as compared to patients with a positive time-domain SAECG (39.3% ± 13.9% vs 43.2% ± 13.6%, $P < 0.02$, respectively). However, there was no difference in patients with a negative spectral turbulence or time-domain SAECG (47.5% ± 14.1% vs 46.5% ± 14.6%, P = NS, respectively).

TABLE 4
Comparison of Diagnostic Criteria

	Sensitivity (%)	Specificity (%)	Positive Predictive Accuracy (%)	Negative Predictive Accuracy (%)	Total Predictive Accuracy (%)
			Cardiac Death		
Standard TD	45	74	11	95	73
Standard STA	53	69	11	95	68
New STA	48	80	15	96	79
			Ventricular Tachycardia		
Standard TD	57	74	7	98	74
Standard STA	52	69	6	98	68
New STA	48	80	8	98	79
			Sudden Arrhythmic Death		
Standard TD	46	74	3	99	73
Standard STA	64	68	4	99	68
New STA	64	80	6	99	79
			Arrhythmic Events		
Standard TD	52	74	9	97	73
Standard STA	55	69	8	97	68
New STA	45	80	10	97	78

Sensitivity, specificity, positive predictive accuracy, negative predictive accuracy, and total predictive accuracy for the prediction of cardiac death, ventricular tachycardia, sudden arrhythmic death, and arrhythmic events are shown for the conventional time-domain criteria (Standard TD), previously published spectral turbulence criteria (Standard STA), and the criteria of normality of spectral turbulence analysis derived in this study (New STA).

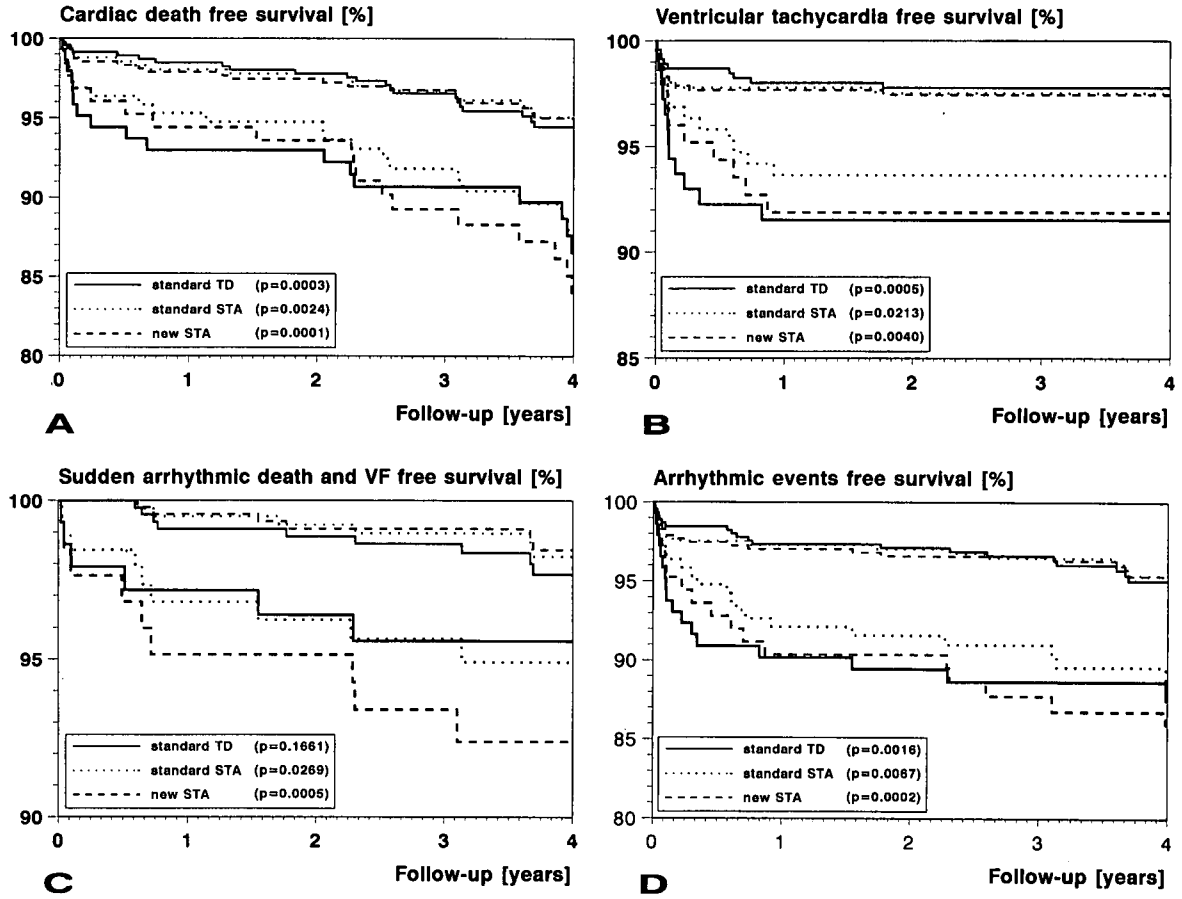

Figure 2. *Kaplan-Meier curves of survival free of cardiac death (A), sustained symptomatic ventricular tachycardia (B), sudden arrhythmic death and/or resuscitated ventricular fibrillation (C), and arrhythmic events (D). Pairs of curves corresponding to subpopulations of patients with normal and abnormal SAECG according to standard time-domain (TD) and standard and new spectral turbulence analysis (STA) criteria are shown with the same pattern; the curves corresponding to patients with normal and abnormal SAECG analysis are shown in light gray and solid black, respectively. In each panel, the inset also shows the probabilistic significance (p) of the distinction between the curves corresponding to given normal and abnormal SAECG analysis.*

Relation Between SAECG Analysis and the Site of Myocardial Infarction

Among patients with a positive spectral turbulence SAECG, according to our new criteria, 56% (71/126) had an anterior myocardial infarction as compared with 41% (67/162) in patients with a positive time-domain SAECG ($P < 0.05$). However, there was no difference in the site of myocardial infarction in patients with a negative SAECG.

Discussion

Our study showed that spectral turbulence analysis of the SAECG was a better predictor of cardiac death than time-domain analysis. However, the two methods were essentially equivalent for the prediction of ventricular tachycardia, sudden arrhythmic death, and arrhythmic events.

Comparison with Previous Studies

Only two studies have addressed the predictive value of spectral turbulence analysis after myocardial infarction.[22,26] Using previously published criteria, Mäkijärvi et al.[22] concluded that spectral turbulence analysis was inferior to time-domain analysis for the prediction of arrhythmic events after myocardial infarction. In their study, spectral turbulence had a sensitivity of only 33% for the prediction of arrhythmic events, compared with 59% for time-domain analysis. However, spectral turbulence compared favorably with time-domain analysis in terms of specificity and predictive ac-

curacy. Ahuja at al.[26] concluded that combination of time-domain and spectral turbulence analysis increases the predictive accuracy of SAECG analysis for postinfarction arrhythmic events. In our study using the same criteria (previously published limits of spectral turbulence analysis), we found that spectral turbulence was inferior to time-domain analysis for the prediction of all four endpoints. However, these spectral turbulence criteria were originally optimized for identification of patients with inducible sustained ventricular tachycardia.[16] Using new criteria derived from the computation of the PPC curves, we improved the predictive characteristics of spectral turbulence analysis after myocardial infarction. Indeed, spectral turbulence compared favorably with time-domain analysis for risk stratification after myocardial infarction.

The MPPS parameter was not included in most previous studies on spectral turbulence analysis. We have also observed a rather poor performance of this parameter in terms of statistical distinction between patients with and without follow-up events. In spite of this, the performance of this parameter in terms of positive predictive accuracy, achieved especially at low levels of sensitivity, was superior to other spectral turbulence indices. We therefore included the MPPS parameter into spectral turbulence analysis in this study as well as into proposed criteria of its normality.

Interpretation of the Results

The conventional time-domain diagnosis of SAECG favors pathologic changes at the end of the QRS complex. Therefore, it is likely to fail to depict arrhythmogenic slow conduction area in the early activated septal and anterior regions. Indeed, time-domain analysis will also not detect other pathologies such as large myocardial scars or ischemic zones with abnormal excitation-conduction. These forms of myocardial pathologies that disturb the general pattern of ventricular activation are likely to be demonstrated by spectral turbulence analysis. Thus, it seems plausible that spectral turbulence analysis is able to detect not only arrhythmogenic substrate but also pathologies that contribute to pump failure. This could explain the superiority of spectral turbulence for the prediction of cardiac death. This hypothesis is further supported by the lower ejection fraction we found in patients with a positive spectral turbulence SAECG as compared to patients with a positive time-domain SAECG.

The fact that spectral turbulence was not found to be superior to time-domain analysis for the prediction of arrhythmic endpoints may have different explanations. It is possible, although not directly supported by our findings, that the principle of spectral turbulence analysis is intrinsically inferior to that of time-domain analysis. This might be caused by the difficulties of applying the Fourier transformation to signals of a biologic rather than of engineering nature for which it is well suited.[27,28] However, spectral turbulence analysis may also be too sensitive and may depict abnormalities in ventricular activation, not all of which will be proarrhythmic. In this respect, time-domain analysis may be more robust than spectral turbulence for the prediction of arrhythmic complications.

The new criteria of normality of spectral turbulence analysis that we derived from computations of PPCs require further validation. In this study, we obtained these criteria from a retrospective analysis of the investigated population. Thus, the particular values of dichotomy limits of individual spectral turbulence parameters might have been influenced by special characteristics of our population. Nevertheless, data collections similar to ours exist in several other centers, and prospective evaluations of the criteria suggested in this study should be easily achievable.

Limitations of the Study

We compared the practical performance of spectral turbulence analysis with one particular setting of time-domain analysis (Del Mar filter with high- and low-pass filters of 40 to 250 Hz) performed by a particular commercial system. It might have been more appropriate to investigate different filter settings of the time-domain analysis performed with different filtering algorithms on different equipment. However, the time-domain analysis offered by different commercial systems has been reported to be fairly consistent,[29] and the high- and low-pass filter settings used in this study are those generally recommended and widely used.[25] Moreover, one of our recent technical studies suggested that the Del Mar filter might be better for postinfarction risk prediction than the more widely used Butterworth filter.[30]

The endpoints we chose can also be debated. Cardiac death was preferred to all-cause mortality because it is unlikely that the analysis of the SAECG might predict noncardiac deaths. Ventricular tachycardia was preferred to a combination of ventricular tachycardia and fibrillation be-

cause the anatomical substrates of these arrhythmias are different.[31] Time-domain analysis of SAECG probably performs better for the prediction of ventricular tachycardia than for ventricular fibrillation. Also, clinical management of patients prone to ventricular tachycardia or to ventricular fibrillation is different. Therefore, ventricular tachycardia alone constitutes an endpoint for which time-domain analysis is a recognized well-performing risk stratifier and for which spectral turbulence has to demonstrate its predictive abilities. Finally, our definition of sudden arrhythmic death was substantially more restrictive than the definition of sudden cardiac death that has been currently used in many studies.[32] For some of the patients who died suddenly, i.e., within 1 hour of the symptoms, clinical or postmortem examination indicated that heart failure or reinfarction was the most likely cause of death. Therefore, to restrict our endpoint to definite arrhythmic events, we excluded these patients in whom the sudden death was unlikely to be primarily arrhythmic.

Conclusion

Spectral turbulence analysis of the SAECG is a better predictor of cardiac mortality than time-domain analysis. However, in our population of postmyocardial infarction patients, it did not perform better than time-domain analysis for the prediction of arrhythmic events. Given the respective abilities for the prediction of cardiac death and arrhythmic events of both analyses as well as their intrinsically different technical natures, it is plausible to speculate that combination of spectral turbulence and time-domain analysis, or, possibly more likely, a combination of selected parameters from both types of SAECG analysis, will prove useful in the future.

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